Comparison between nuclear thermometers in central Xe+Sn collision

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Abstract The temperature of fragmenting source in central heavy-ion collisions at Fermi energy is investigated by the isospin-dependent quantum molecular dynamics model in combination with the statistical decay model GEMINI. Five different nuclear thermometers are used to extract nuclear temperature. We find that the He and Li isotope temperature reaches a plateau at about 70–100 MeV/nucleon of beam energy. The slope temperature and the quadrupole fluctuation temperature give high values. The quantum slope temperature and the quantum quadrupole fluctuation temperature are more close to the He and Li isotope temperatures.

Key words Heavy-ion collision, Nuclear temperature, Phase transitions

1 Introduction

The nuclear matter may undergo a phase transition from the liquid ground-state to a gas of nucleons when the nuclei was heated. The nature of the interaction between nucleons is similar to the Van der Waals forces between molecules. The uncertainties of the nuclear equation of state (EOS) make the study of nuclear liquid-gas phase transition be important and meaningful[1,2]. Experimental signals of phase transitions have been observed by many experimental groups[3-6]. Many theoretical efforts to find signatures of phase transitions in heavy-ion collisions (HICs) have been performed a few years ago[7-9]. HICs at intermediate energies offer an opportunity to heat nuclei, and the nuclear multifragmentation is long assimilated to the nuclear liquid-gas phase transition.

Temperature is one of the most important degrees of freedom in describing phase transition. However, the nuclear matter created in HICs is a non-equilibrium, finite, and open system. It is more difficult to determine the temperature in nuclear matter than that in ordinary matter. Different from ordinary thermometer, nuclear thermometers are more complicated. Several nuclear thermometers have been proposed in the past days. These approaches can be divided into three families[2,10]: (1) Kinetic approach. Kinetic approach is based on the assumption that energy spectra of particles obey the Maxwell-Boltzmann distribution. The temperature can be derived from the slopes of the kinetic energy spectra[11,12] or the momentum fluctuations[13]. It has been suggested that the slopes of light product spectra in nuclear reactions lead to very high “temperatures”. The temperatures extracted from Maxwell-Boltzmann kinetic approach probably reflect not only the thermal properties of the system, but also the collective energies coming from the dynamics of the nuclear collision. Recently, the Fermi-Dirac kinetic approach is considered to improve this type of thermometer[14,15]. (2) Population approaches. The underlying idea for this method is that the relative populations of the produced clusters or its excited states are assumed to obey a Boltzmann distribution. Population of excited

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states[16] and double ratios of isotopic yields[17] are two of the most often used methods. Employing the isotopic thermometer, Pochodzalla *et al*. had given the caloric curve which is taken as the evidence of the occurrence of a liquid – gas type phase transition[4]. (3) Thermal-energy approaches. The temperatures at freeze-out are obtained from the excitation energy which is extracted by measuring evaporation cascade from a thermalized source by varying neutron-to-proton ratio *N*/*Z*. An example is the isospin thermometer[18].

In this paper, we attempt to compare five different nuclear thermometers. The central collisions of ^{129}Xe+ ^{120}Sn at Fermi energy are simulated by the isospin-dependent quantum molecular dynamics (IQMD) model together with the statistical decay code GEMINI. The double ratio temperature, the slope temperature, the quantum slope temperature, the quadrupole fluctuation temperature, and the quantum quadrupole temperature are compared.

2 IQMD transport model

The IQMD model[19,20] is based on the same principles as the quantum molecular dynamics model. With consideration of the different mean field potentials of proton and neutron, and the production of pion and kaon, the IQMD model has been widely and successfully used for the analysis of collective flows, stopping, pion and kaon multiplicities in HICs at incident energy below 2 GeV/nucleon[20]. The statistical code GEMINI was proposed by R. J. Charity in 1980s[21]. It can be utilized to treat the decay of a compound nucleus in fusion reaction and excited fragments in HICs. GEMINI code was always applied to the transport model to statistically deexcite the hot fragments[22]. Recently, within the framework of the IQMD + GEMINI model, the odd-even effect in the yields of the final fragments has been well reproduced[23]. Using the same model we have investigated the multiplicities and the kinetic energy spectra in central HICs, the simulations are in very good agreement with the experimental data. The slope temperature and the isotope temperature were also studied[14,24]. The transport with modified (the medium factor of $1-0.2\rho/\rho_0$) nucleon-nucleon elastic cross section[25] and soft EOS[26] are used to study the nuclear temperature. To compensate the fermionic feature the method of the phase-space density constraint in the constrained molecular dynamics model[27] is applied.

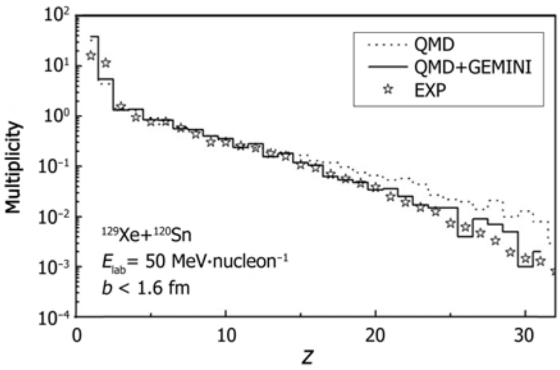

Fig.1 Charge distributions of fragments produced in central collisions of ^{129}Xe+ ^{120}Sn at 50 MeV/nucleon.

3 Results and discussion

3.1 He and Li isotope temperature

Figure 1 displays charge distribution of the central collision ($b<1.6$ fm) of ^{129}Xe+ ^{120}Sn at 50 MeV/nucleon. Both the simulation by IQMD with and without GEMINI code are displayed in the figure. The experimental data are shown by the symbol. Firstly, it is clearly seen that IQMD + GEMINI can reproduce the experimental data quite well. Secondly, with the help of GEMINI code, the yield of heavier fragments will decrease and that of light particles will increase, due to deexcitation of the hot fragments. The good agreement with experimental data, makes the study of the double ratio temperature be possible and believable. We introduce one of double ratio temperature in which He and Li isotopes are used, named $T_{\rm HeLi}$. It is defined by

$$T_{\rm HeLi}=13.3\,{\rm MeV}/\ln\left(2.2\frac{Y_{^6{\rm Li}}/Y_{^7{\rm Li}}}{Y_{^3{\rm He}}/Y_{^4{\rm He}}}\right), \tag{1}$$

where Y is the yield of the isotope. The $T_{\rm HeLi}$ can be calculated using this formula.

3.2 The slope and the quantum slope temperature

Figure 2 illustrates the calculated (open circle) and experimental (open star) kinetic energy spectra of free protons in central collisions of ^{129}Xe+ ^{120}Sn at $E_{\rm lab}$ = 50 MeV/nucleon. The solid lines in each panel

denote Maxwell-Boltzmann fit. The fit formula is expressed as

$$Y(E) \propto \frac{(E-E_0)}{T_{\text{slope}}^2} \exp\left(-\frac{(E-E_0)}{T_{\text{slope}}}\right), \tag{2}$$

where E_0 reflects the repulsive Coulomb forces[27]. Taking into account the Fermi nature of nucleon, the slope temperature was rewritten by Bauer[29]

$$T_{\text{slope}} = \frac{A-A_f}{A-1}\frac{2}{5}E_F\left(1+\frac{5\pi^2 T_{\text{slope}}'^2}{12E_F^2}\right), \tag{3}$$

where E_F is the Fermi energy. T'_{slope} names the quantum slope temperature.

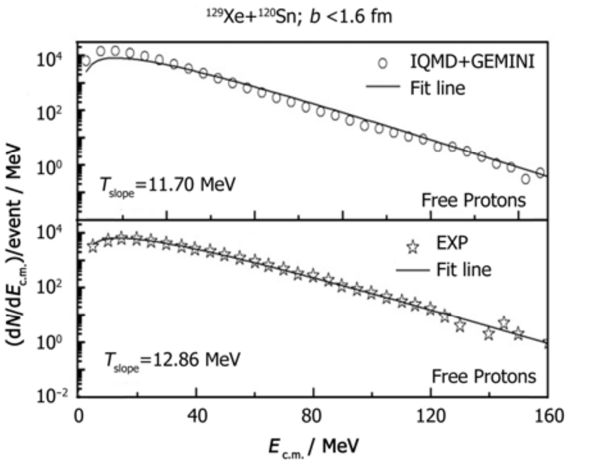

Fig.2 Center of mass kinetic energy spectra of free protons produced in central collisions of ^{129}Xe+^{120}Sn at $E_{\text{lab}}=50$ MeV/nucleon.

3.3 Quadrupole fluctuation and the quantum quadrupole fluctuation temperature

One of new nuclear temperature which is based on momentum fluctuations of detected particles was proposed in Ref.[17]. The momenta of particles were assumed to obey the Maxwell-Boltzmann distribution

$$f(p) = \frac{1}{(2\pi m T_{\text{fluct}})^{3/2}} \exp\left(-\frac{p_x^2+p_y^2+p_z^2}{2mT_{\text{fluct}}}\right), \tag{4}$$

where m is the mass of the particle, p_x, p_y and p_z are three momentum components of the particle. The variance σ_{xy}^2 can be obtained from the quadrupole $Q_{xy} = p_x - p_y$ distribution through

$$\sigma_{xy}^2 = \int d^3 p \left(Q_{xy}\right)^2 f(p). \tag{5}$$

Figure 3 shows the distribution of Q_{xy} for free protons. The form is similar to the experimental results[13]. Then, we can get the T_{fluct} from these formulae, the results are shown in Fig.4. More details will be discussed in the following section. The fluctuation temperature was improved as follows[18]:

$$T_{\text{fluct}} = \sqrt{\frac{4E_F^2}{35} + \frac{2\pi^2}{15}T_{\text{fluct}}'^2}, \tag{6}$$

where E_F is the Fermi energy of nuclear matter and T'_{fluct} is named as the quantum quadrupole temperature.

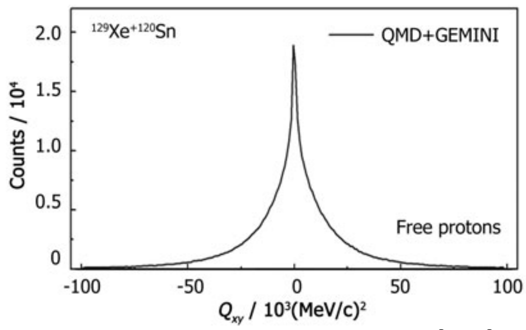

Fig.3 Distributions of quadrupole $Q_{xy} = p_x^2 - p_y^2$ for free protons produced in central collisions of ^{129}Xe+^{120}Sn at $E_{\text{lab}}=50$ MeV/nucleon.

3.4 Comparison between nuclear thermometers

Within the IQMD+GEMINI model, we calculated the nuclear temperatures from ^{129}Xe+^{120}Sn central collision at incident energies from 30 MeV/nucleon to 100 MeV/nucleon. Five nuclear thermometers are investigated in this work: the double ratio temperature T_{HeLi}, the slope temperature T_{slope}, the quantum slope temperature T'_{slope}, the quadrupole fluctuation temperature T_{fluct}, and the quantum quadrupole temperature T'_{fluct}. The results are shown in Fig.4.

Firstly, it can be seen that different thermometers give very different values of nuclear temperature. The discrepancy between various nuclear temperature steadily grows with increasing incident energy. All temperatures exhibit an increase of value with increasing incident energy. T_{HeLi} reaches a plateau at about 70–100 MeV/nucleon of beam energy. Secondly, T_{slope} and T_{fluct} are very close to each other, because both of these two approaches assumed energy distribution (Eq.(2)) and the momentum distribution (Eq.(4)) are the classical Maxwell-Boltzmann type. These two temperatures are the highest of all. It is because besides the thermal motion, they also contain the Fermi motion. Thirdly, T'_{slope} and T'_{fluct} are both smaller than T_{slope} and

$T_{\rm fluct}$. This is because the Fermi motion of nucleon is removed. But due to the different methods of elimination of the Fermi motion, the results are different.

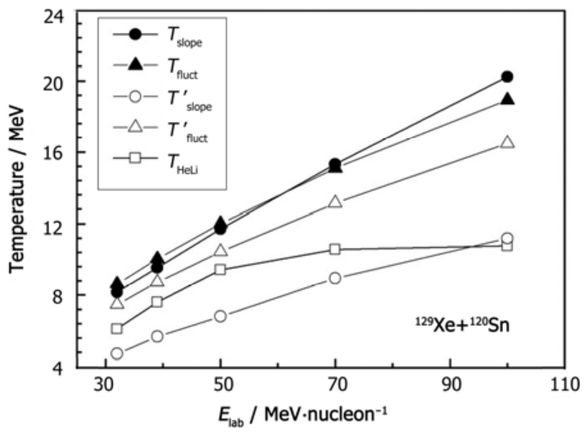

Fig.4 Nuclear temperatures extracted from various methods as a function of incident energies for central collisions of ^{129}Xe+ ^{120}Sn.

4 Conclusion

Within the IQMD+GEMINI model, various nuclear thermometers have been investigated for the central collisions of ^{129}Xe+^{120}Sn at incident energy range from 30 to 100 MeV/nucleon. These nuclear thermometers are not exactly coincident with each other. The He and Li isotope temperature reaches a plateau at about 70–100 MeV/nucleon of beam energy. The slope temperature and the quadrupole fluctuation temperature give higher values than others. This is because the Fermi motions of nucleons are not eliminated. The quantum slope temperature and the quantum quadrupole fluctuation temperature are more close to the He and Li isotope temperature because of the removed Fermi motion.

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